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Miniature Drag-Force Anemometer

L. N. Krause and G. C. Fralick
Lewis Research Center
Cleveland, Ohio

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MINIATURE DRAG-FORCE ANEMOMETER

L. N. Krause and G. C. Fralick
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

ABSTRACT

A miniature drag-force anemometer is described which is capable of measuring unsteady as well as steady-state velocity head and flow direction. It consists of a cantilevered beam with strain gages located at the base of the beam as the force measuring element. The dynamics of the beam are like those of a lightly damped second-order system with a natural frequency as high as 40 kilohertz depending on beam geometry and material. The anemometer can be used in both forward and reversed flow. Anemometer characteristics and several designs are presented along with discussions of several applications.

INTRODUCTION

This paper describes a miniature drag-force anemometer, consisting of a cantilevered beam with attached strain gages, which is capable of measuring unsteady velocity head and flow direction in a gas stream. The instrument was developed because the assortment of available instruments for determining unsteady flow quantities such as total pressure and velocity is limited and because measuring time-varying phenomena has become increasingly important in the developmental testing of airbreathing engines and their components.

The major types of unsteady flow diagnostic instrumentation in current use are miniature pressure transducers, mounted either in probes or duct walls, hot-wire and hot-film anemometers, and laser anemometers.

The use of the laser anemometer is becoming more common because of the nonintrusive nature of the instrument. It is especially useful in transonic flows where probe blockage is excessive and also in velocity surveys in the passages between rotating blades. High cost and the requirement of optical access are the main factors limiting the application of laser anemometer systems.

Hot-wire and hot-film anemometers are also used to determine unsteady velocity. However, these instruments have a number of serious shortcomings. When used in compressible flows where density and temperature variations are not negligible, the aneometers require an elaborate calibration, and even with a complete calibration, interpretation of results is difficult. Wire breakage, and change in calibration due to flow contamination and/or corrosion are also problems. Each anemometer channel also requires an elaborate electronics package.

The drag-force anemometer has the potential of overcoming some of the shortcomings of the hot-wire and hot-film anemometers. It is more rugged than a hot-wire anemometer, and its calibration is simple and unaffected by flow contamination, and associated electronics are as simple as those of strain gage pressure transducers.

There is little reported literature on the type of drag-force anemometer reported herein. The earliest reported use for unsteady flow measurement was in 1970 in which it was used in compressor rotating stall experiments (ref. 1). We at the Lewis Research Center have reported on some of our work with the anemometer in references 2, 3, and 4. This paper summarizes our work with the anemometer (1975 to present) including several examples of applications.

DESCRIPTION OF ANEMOMETERS

A photograph of three designs of drag-force anemometers is shown in figure 1. Probe A consists of a silicon beam (which is commercially available) 0.25 mm thick with an unsupported length of 2.5 mm with the outer 1.5 mm exposed to the flow. A four-arm diffused strain gage bridge is on one side of the beam at the base. Because silicon is brittle like glass, the

anemometer is fragile, and care is required in handling. Details of probe A are given in reference 2. Probe B consists of a stainless-steel beam 0.1 mm thick with other dimensions the same as probe A. A complete bridge (two semiconductor strain gages on either side of the beam) is epoxy bonded at the base of the beam. Probe C has a 0.12 mm thick beam and un unsupported length of 25 mm with 12.5 mm exposed to the flow and has foil strain gages.

PRINCIPLE OF OPERATION

Velocity Head Measurement

The principle of operation can be described with reference to figure 2. The drag force, D, on the beam for flow normal to the beam surface is given by

$$D = C_D \frac{\rho U^2}{2} A \tag{1}$$

For constant beam area A, and constant drag coefficient C_D, the drag force is proportional to the velocity head $\rho U^2/2$, where ρ and U are fluid density and velocity, respectively. The drag force is related to the electrical output of the strain gages located at the base of the beam. The drag coefficient is relatively insensitive to flow angle for angles to within 20° of normal to the beam surface. Effects of variation in Reynolds number on drag coefficient are small for Reynolds number greater than 10,000 (ref. 5). Effects of variation in Mach number are also small for Mach numbers less than 0.75 (ref. 5). However, at transonic Mach numbers, variations in drag coefficient are not negligible and cause a nonlinear relation between drag force and velocity head.

It should be noted that the drag-force anemometer can measure either forward or reverse flow. However, velocity can only be obtained from the velocity head when variations in density are negligible.

Flow Direction Measurement

If the beam is oriented so that flow is nearly parallel to the beam surface, the drag coefficient is porportional to the flow angle, as shown in figure 2. (Strictly speaking, the term "drag coefficient" should be replaced with "lift coefficient" in this region.) The output of the strain gages for this case is proportional to both flow angle and velocity head; so, that when flow direction is measured, either two beams must be used or a single beam must be rotated to two positions (flow nearly normal and flow nearly parallel to the beam surface). An alternate method of determining flow angle sensitivity is an in situ calibration which can be done if the anemometer can be rotated to known angular positions.

SENSITIVITY

Velocity Head Measurement

For a beam of thickness t, unsupported length L, and Young's modulus of the beam material E, the sensitivity as derived in reference 2 can be expressed as

$$\text{Sensitivity} \propto \frac{GL^2}{Et^2} \frac{\rho U^2}{2} \tag{2}$$

The factor G includes both the strain gage factor and also the number of active gages in the strain gage bridge. G for four active gages is twice that for two active gages, and the gage factor for semiconductor gages is about an order of magnitude greater than that of foil or wire gages. A more complete expression for sensitivity which includes variable location for the strain gages (the gages are normally located as close to the base of the beam as is practical) is given in reference 2. The relative sensitivities of the probes of figure 2 (normalized to probe A) are given in table I. A typical calibration curve (for probe C of fig. 1) from which sensitivity is determined is shown in figure 3. The calibration was obtained by testing the anemometer over a range of velocities in the isentropic core of a free jet at ambient temperature. The value of the sensitivity in the forward flow direction can be slightly different from that of reversed flow because of nonsymmetry in strain gage application and/or beam geometry. If inaccuracies less than 10 percent in sensitivity (5 percent in velocity) are desired for cases where both forward and reversed flow are of interest, then the anemometer should be calibrated with flow in both directions. The anemometer is quite inesnsitive to angular misalignment for nearly normal flow incidence. The output voltage is essentially constant over a range of ±20° from normal.

Flow Direction Measurement

Flow angle sensitivity of probe C (from fig. 2) is shown in figure 4. Since probe C is a thin beam with symmetrical strain gage patterns on either side of the beam, the flow angle sensitivity curve is symmetrical. However, for a probe such as A where the beam is relatively thick compared to its width (1/6), and the strain gages are all located on one side of the beam, the flow angle sensitivity curve is unsymmetrical and also insensitive near zero angle (ref. 2). For the latter, the probe must be approximately aligned on a usable part of the sensitivity curve. The slope of the sensitivity curve of figure 4 is approximately the same as a calculated slope based on the curve of figure 2.

FREQUENCY RESPONSE

Natural Frequency

The drag-force anemometer is a simple plane beam, supported at one end and free at the other. Its motion can be described by the wave equation for thin beams (ref. 6). The natural frequency, f_n, for an ideal beam in the first bending mode is

$$f_n \propto \frac{t}{L^2}\sqrt{\frac{E}{\rho}} \tag{3}$$

where ρ is the density, the mass per unit volume. The ratio E/ρ is called specific stiffness and is used as a means of extending the frequency response. Specific stiffness for silicon is about three times that of steel.

In contrast to the situation for an ideal beam, there is a certain amount of damping present. The amount of damping is characterized by the parameter ζ, called the fraction of critical damping or damping coefficient. It is equal to zero for an ideal (undamped) system and has the value 1 for a system which is critically damped.

The two parameters which characterize the beam, f_n and ζ, can be measured by using a spectrum analyzer. For a lightly damped second-order system, such as the drag-force anemometer considered in this report, the frequency spectrum of the strain gage signal is relatively flat at low frequencies, rises to a maximum at a frequency f_n, and finally drops off at higher frequencies. This is true as long as beam excitation can be characterized as a white noise source, a source whose spectrum is continuous and uniform as a function of frequency.

The natural frequencies for the probes of figure 1 are given in table I. The damping coefficient of probe A is about 0.01 and about 0.03 for probe B, so that the beams can be considered highly underdamped.

It should be noted from relation 3 that a short thick beam is required for high-frequency response (high f_n), and that a long thin beam is required for high sensitivity (relation 2).

Velocity Derivative

The drag-force anemometer in steady flow has an output proportional to velocity head. If the flow is unsteady, fluid mechanics suggests that an additional term proportional to the rate of change of velocity is also present.

A beam-type anemometer is a second-order system and thus satisfies a differential equation of the type

$$\frac{\ddot{x}}{\omega_n^2} + 2\zeta\frac{\dot{x}}{\omega_n} + x = \kappa D(t) \tag{4}$$

where $\omega_n = 2\pi f_n$, ζ is the damping coefficient, and x is the output signal. κ is a proportionality constant having units mV/N. For steady flow, or if the velocity derivative effect is negligible, $D(t) = C_D A[(1/2)\rho U^2]$. If the velocity derivative effect cannot be ignored, $D(t)$ might be written $D(t) = C_D A[(1/2)\rho U^2] + C(dU/dt)$. The additional term could be a source of error when measuring a rapidly varying flow, as in a jet engine.

An attempt was made to find the effect of any velocity derivative term in the output of a silicon beam drag-force anemometer, such as the one shown in figure 1. This extra term will change the frequency response curve in a known way, so that the magnitude of the parameter describing the velocity derivative can be determined by finding the best fit to an experimental curve. A typical measured frequency response curve (corrected for the frequency characteristics of the open jet in which the anemometer was run) together with the curve fitted to it is shown in figure 5.

From the results of such measurements, the average value for the velocity derivative parameter turned out to be zero, leading to the conclusion that at least for the frequencies and probe geometries involved, any velocity derivative effect can be ignored. More details are given in reference 4.

Extending the Frequency Response

As explained in the previous section, the electrical output of the drag-force anemometer, x, satisfies the second-order differential equation (4). The object of the measurement is using the probe output to obtain information about D(t), which characterizes the flow.

For frequencies small compared to ω_n, the first two terms may be ignored, and $x \approx \kappa D(t)$. In this case little error is introduced by the probe. For measurements of higher frequency phenomena, however, probes of higher and higher natural frequency must be developed, but this places limitations on the sensitivity, as explained in an earlier section.

This leads to the idea of electronic compensation (ref. 7). The compensator electronically performs the operations in equation (4) and recovers the original signal, D(t). This is shown schematically in figure 6.

The frequency response of an anemometer with a natural frequency of 1330 Hz and damping coefficient of 0.02 is shown in figure 7. The compensated response of the probe is flat to withn 7 dB to well beyond twice the natural frequency. The use of a compensator does, however, introduce additional noise into the output signal.

ZERO DRIFT AND SENSITIVITY STABILITY

The accuracy of the drag-force anemometer reported herein is limited by the zero drift and sensitivity stability characteristics of the strain gage systems used as well as the technique used to mount the beams. Three systems were used. Probe A consisted of a silicon beam (expansion coefficient of $2.5 \times 10^{-6}/^\circ C$) with a diffused strain gage bridge on one side only. The beam was bonded (bond joint on one side) to a stainless-steel mount (expansion coefficient of $18 \times 10^{-6}/^\circ C$) with an epoxy whose coefficient was about 90×10^{-6} per °C. Probe B consisted of a stainless-steel beam with two semiconductor strain gages epoxy bonded at the base of the beam which, in turn, has one side epoxy bonded to a stainless-steel mount. Probe C consists of a stainless-steel beam with two foil strain gages (matched for the expansion coefficient of stainless steel) bonded at the base of the beam which has both sides epoxy bonded to a stainless-steel mount. The strain gages of probes A and B are limited to a recommended operating temperature of 120° C and those of probe C to around 230° C.

In use the beam can be subjected to thermal stresses in the region of the strain gages because of the differences in thermal expansion between the beam, the metal support, and the epoxy which bonds the beam to the support. The zero drift associated with the thermal expansion problem can be minimized by setting the zero on the anemometer before each run and checking it immediately following the run. Preferably, zero settings should be made with the beam at fluid temperature of intended use. When the results shown in figure 3 were generated, in a nearly ambient-temperature air jet, zero drift was small (~0.01 mV/V). This is because of the symmetry of the design plus the good beam-gage expansion match. However, probe A could have a zero drift several times that cited above.

If only the unsteady portion of the velocity head is of interest in a particular application, zero drift is of no concern. However, the stability of the sensitivity is of concern for both steady-state and unsteady applications. An example of significant sensitivity change occurred in a jet engine application in which probe A was exposed to a temperature in excess of 150° C, resulting in a permanent decrease in sensitivity of 30 percent. Whenever a drag-force anemometer is applied to a harsh environment such as a jet engine, the sensitivity should be checked after exposure to verify accuracy.

The full-scale error due to the 0.01 mV/V zero drift mentioned above is about 3.3 percent, or about 1.7 percent velocity error (since the output is proportional to velocity squared). If, as recommended, the zero drift is taken into account, the random error in the velocity measurements is about 0.3 percent of full scale.

The zero drift and sensitivity stability of the drag-force anemometer could be greatly improved by using sputtering technology in applying the strain gages, as well as by eliminating epoxy bonding in mounting the beams.

APPLICATIONS

Several applications are presented to illustrate the usefulness of the drag-force anemometer. Although the applications have been limited to full-scale jet engine and component testing, the anemometer should also be useful in other areas of experimental fluid mechanics.

Compressor Control Dynamics Experiment

The experiment consisted of a small (11 cm diam) multi-stage axial flow compressor and a fast operating valve (~500 Hz response) which was situated downstream of the compressor and subjected the compressor to unsteady flow. Several probes of type A (fig. 1) were used to measure unsteady velocity head at several stations within the compressor. In addition, a probe of type C (fig. 1) was used to measure the unsteady velocity head approaching the compressor. Probe C type was used in the inlet for two reasons. An accurate steady-state as well as unsteady measurement was required, and, because the inlet air velocity was low (less than 100 m/s) an anemometer with good sensitivity was required. The anemometers within the compressor were used to sense stall and how stall propagated throughout the compressor.

Jet Engine Unsteady Flow Generator

In another application similar to the one discussed above, a rotating dynamic flow generating valve was tested on the upstream section of a piping system which simulated a full-scale jet engine. Several drag-force anemometers of probe B type (fig. 1) were used to measure unsteady flow within the piping system. Metal beams were required because of anticipated rust particles in the air from the walls of upstream piping. Furthermore, the probes were actuated into the airstream only when a test point was recorded. Frequency response requirements (several kHz) in addition to small unsteady flows of interest (as small as 1 kPa peak-to-peak) dictated the use of a short beam (for high response) with silicon strain gages (for high sensitivity).

Turbofan Bypass Ducts Unsteady Flow Measurement

The probe shown in figure 8 was used to measure unsteady flow in the bypass ducts of a turbofan engine. Requirements were for 1 kHz response and the ability to measure flow reversals. The probe shown in figure 8 is similar to probe C of figure 1 but with a beam length of 9 mm and a thickness of 0.4 mm. The beam natural frequency was over 4 kHz. The anemometers (two were used) were subjected to the flow transients associated with several dozen engine stalls and operated satisfactorily.

Turbine Unsteady Flow Angle Measurement

In another application, the unsteady flow direction at a measuring station (fig. 9(a)) downstream of an aircraft-type turbine under test was required to insure that the total pressure probes (used for efficiency determination) were not subjected to excessive flow angles. A probe of type A (fig. 1) was used. Results presented in figure 9(b) show that the unsteady flow angle was too small to influence the accuracy of the total pressure probes. In this application an in situ angle sensitivity calibration was performed. With the turbine at a desired set point, anemometer time traces were taken with the beam oriented at three different angular positions from which sensitivity was determined. The traces were synchronized in time via a once-per-revolution signal generator on the turbine shaft. Additional details of the measurements are given in reference 3.

Turbofan Engine Flutter Tests

In this application the anemometer was used as a diagnostic instrument to aid in determining possible changes between flutter and nonflutter flow conditions of the first fan rotor of a turbofan engine. Typical results are shown in figure 10. Figure 10(a) shows the variation in steady flow angle for several blade passages. The blade passing frequency is about 5 kilohertz. Figure 10(a) is the profile obtained by averaging 64 time traces of the same blade passages. The ordinate in figure 10(b) is proportional to the power spectral density of the anemometer output signal. The largest peak represents the blade-passing frequency. There are frequencies present in figure 9(b) which are not multiples of the engine speed, and can be correlated to flutter frequencies. Reference 8 discusses the flutter experiments.

Turbofan Inlet Flow Angle Measurement

In this application the unsteady, as well as the steady, components of flow angle were required in the inlet of a turbofan engine during transient flow conditions. To determine unsteady flow angle of a nonrepetitive nature with the drag-force anemometer, two beams are required. Such a probe is shown in figure 11. The output of the beam, which is approximately parallel to the flow is proportional to both flow angle and velocity head. The output of the

beam which is normal to the flow is proportional to just velocity head, so the flow angle at any instant can be obtained by dividing the outputs.

Turbulence Measurement

To demonstrate the ability of the drag-force anemometer to measure turbulence intensity, an A-type probe (fig. 1) was compared with a hot-wire anemometer in a room temperature air jet. Turbulence intensity from drag-force anemometer readiangs is simply the rms value of the strain gage bridge output divided by twice the mean value (ref. 2). On the jet centerline 0.6 jet diameters downstream from the start of the jet, both a hot-wire and a drag-force anemometer measured an intensity of 1.8 percent. AT 2.3 diameters from the start of the jet and 0.2 diameter from the centerline, the hot-wire anemometer measured a 4.3-percent intensity and the drag-force anemometer measured 3.8 percent intensity.

In the above mentioned applications, probe contamination and dirt buildup were not a problem, although some of the probes had a slight vapor-blast appearance after use. If the probe is to be used in a contaminated environment, it should be mounted in an actuator and inserted into the flow no longer than is required to make the measurement. Further, a metal beam should be considered for such an application, since it is less likely than the silicon type to be damaged by any solid material in the gas stream.

CONCLUDING REMARKS

The drag-force anemometer reported herein has been used to measure unsteady and steady-state velocity head and flow direction in several applications associated with jet engine and engine component research. It has proved especially useful in experiments that include possibilities of flow reversals.

The combination of features which favor the anemometer for the above applications include the ability to measure reversed flows, that the instrument can be made small and rugged, that its acquisition electronics are as simple as those of a strain gage pressure transducer, and that it is of moderate cost. Negative features of the anemometer include the following: the anemometer would be of limited use in flow regions where the drag coefficient of the beam is changing rapidly with velocity (transonic region); because the anemometer is lightly damped, it is difficult to reduce the 'ringing' in the output signal to a negligible amount in some applications; the anemometer has 'flow blockage' effects (because it is an intrusive probe-type device), and output zero drift is a problem when using semiconductor strain gages (the use of sputtering technology for gage application should reduce zero drift considerably).

Because of the combination of the above features associated with the drag-force aneometer, it should find application in the future in several areas of experimental fluid mechanics.

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TABLE I. - SENSITIVITY AND NATURAL FREQUENCY

Probe	Beam	Size		Relative sensitivity	Natural frequency, kHz
		t, mm	L, mm		
A	Silicon, diffused gages	0.25	2.5	1	40
B	Stainless, bonded silicon gages	0.10	2.5	4	10
C	Stainless, bonded foil gages	0.12	25	15	0.2

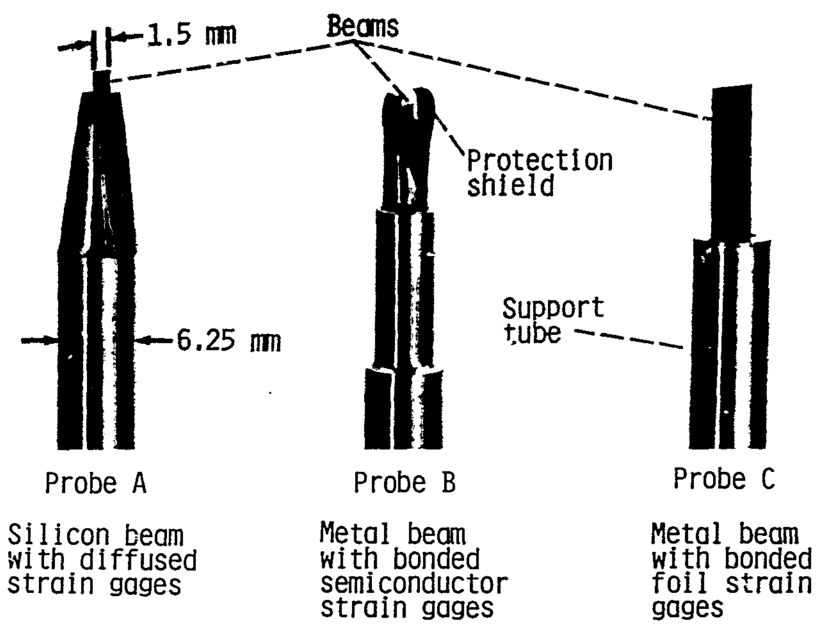


Figure 1. - Drag-Force anemometers.

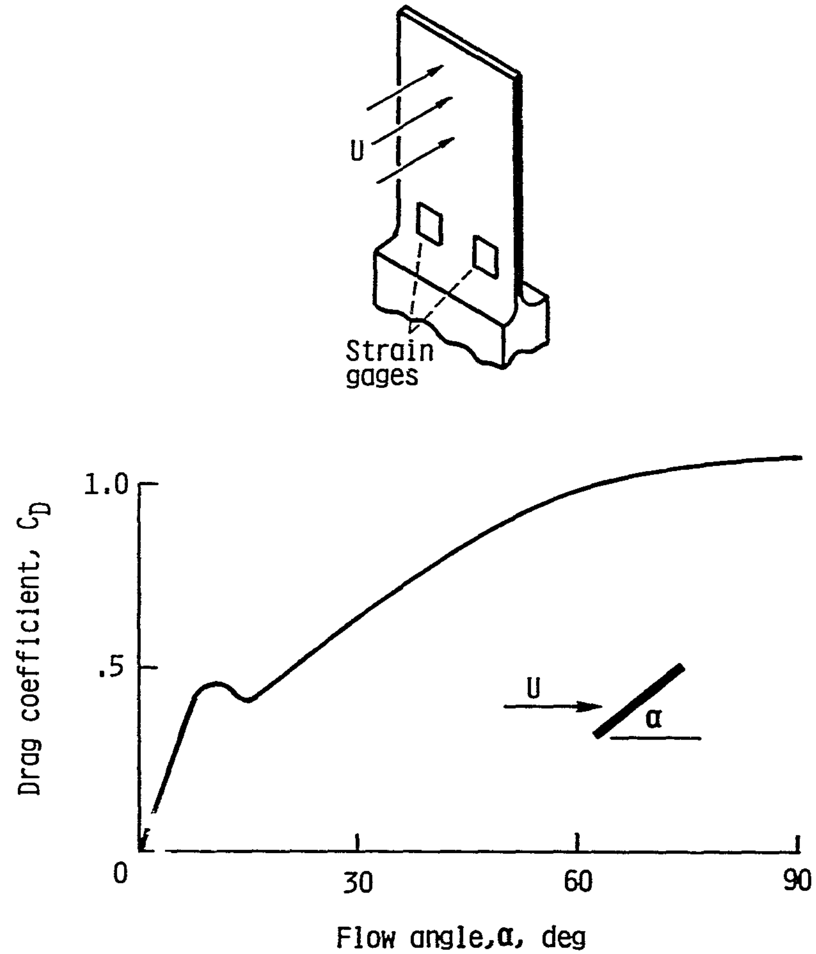


Figure 2. - Principle of operation

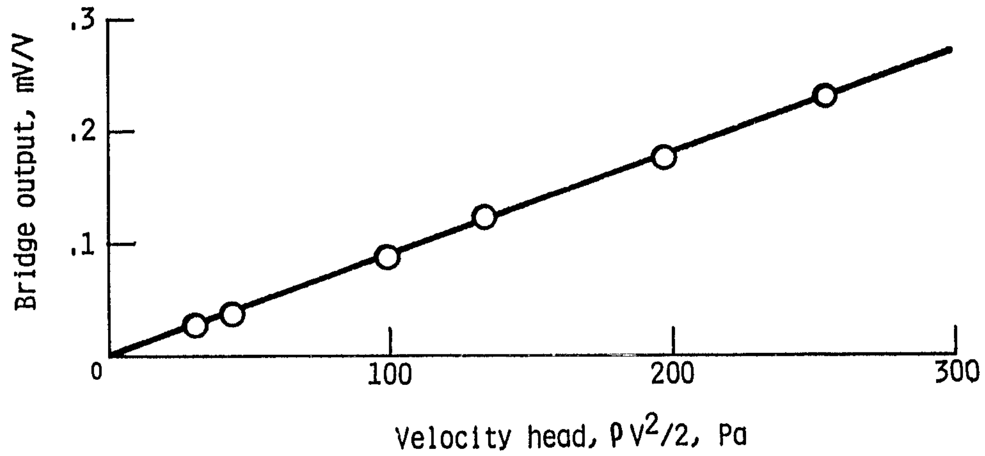


Figure 3. - Drag-force anemometer sensitivity for probe C of figure 1 (1 atm. ≈ 10^5 Pa).

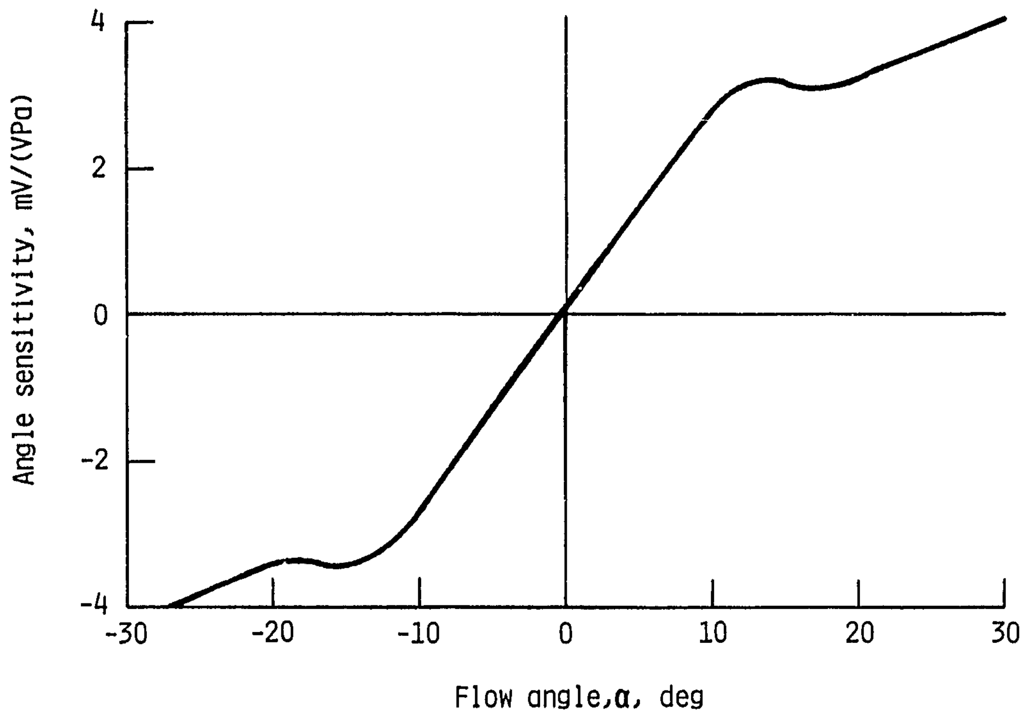


Figure 4. - Flow angle characteristics of Probe C. Sensitivity is in millivolts output per volt input to bridge per pascal velocity head.

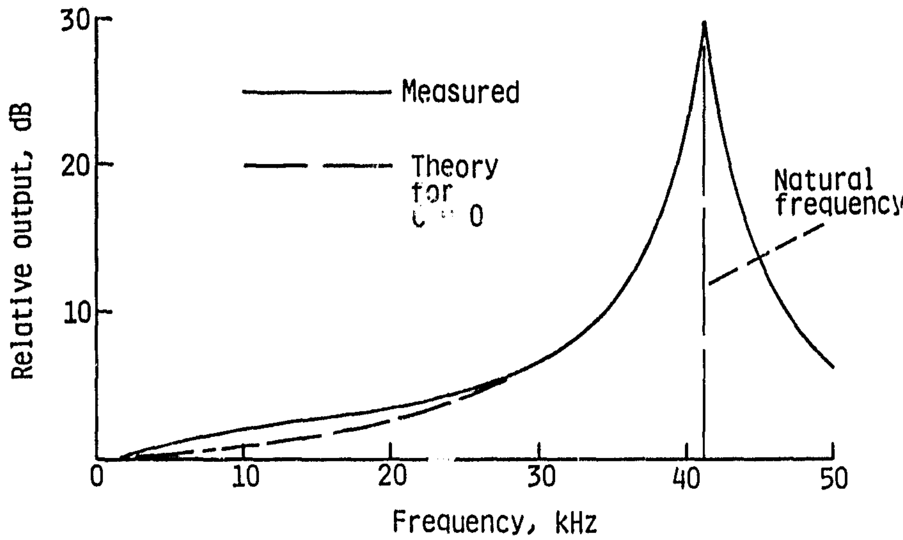


Figure 5. - Effect of velocity derivative term on frequency response.

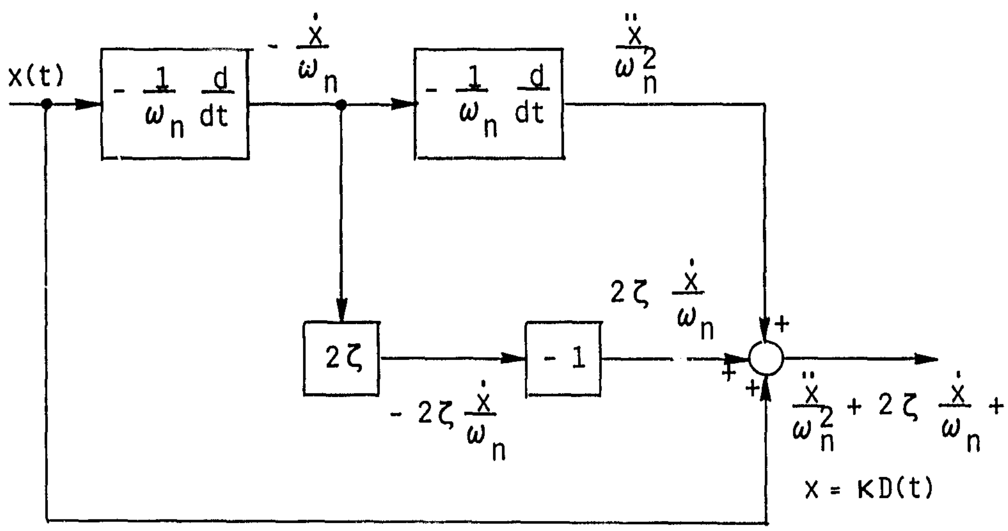


Figure 6. - Block diagram of compensator to extend frequency response.

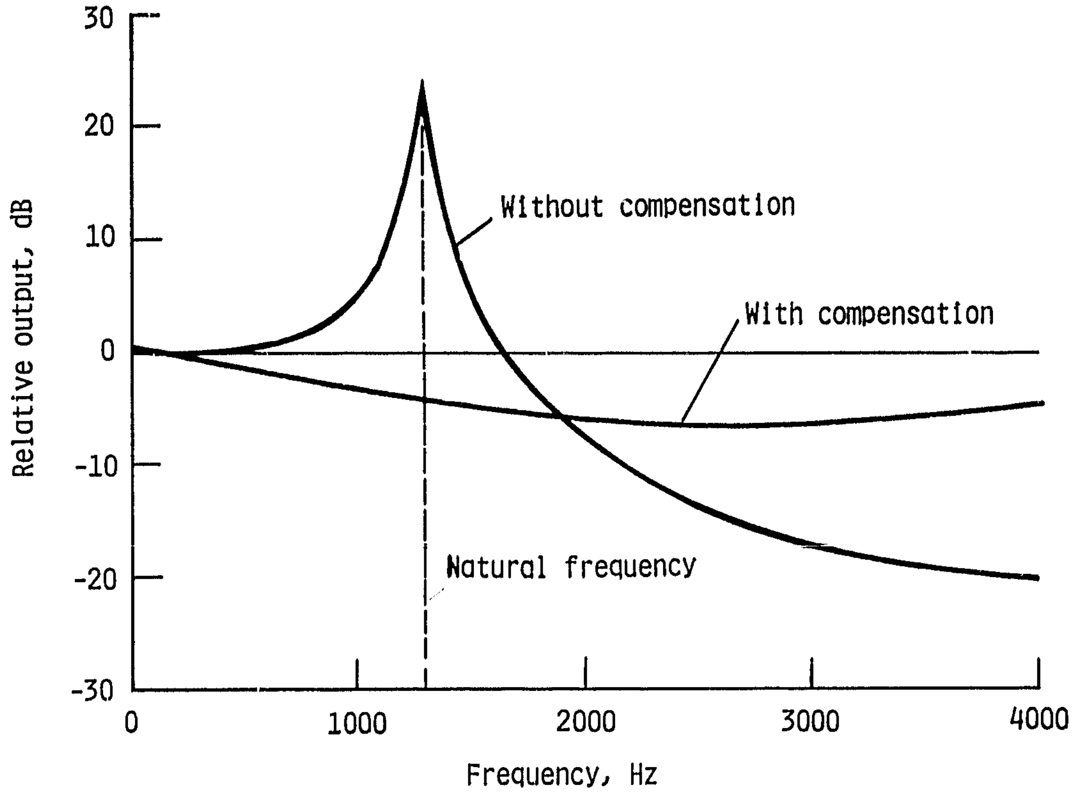


Figure 7. - Frequency response with and without compensation.

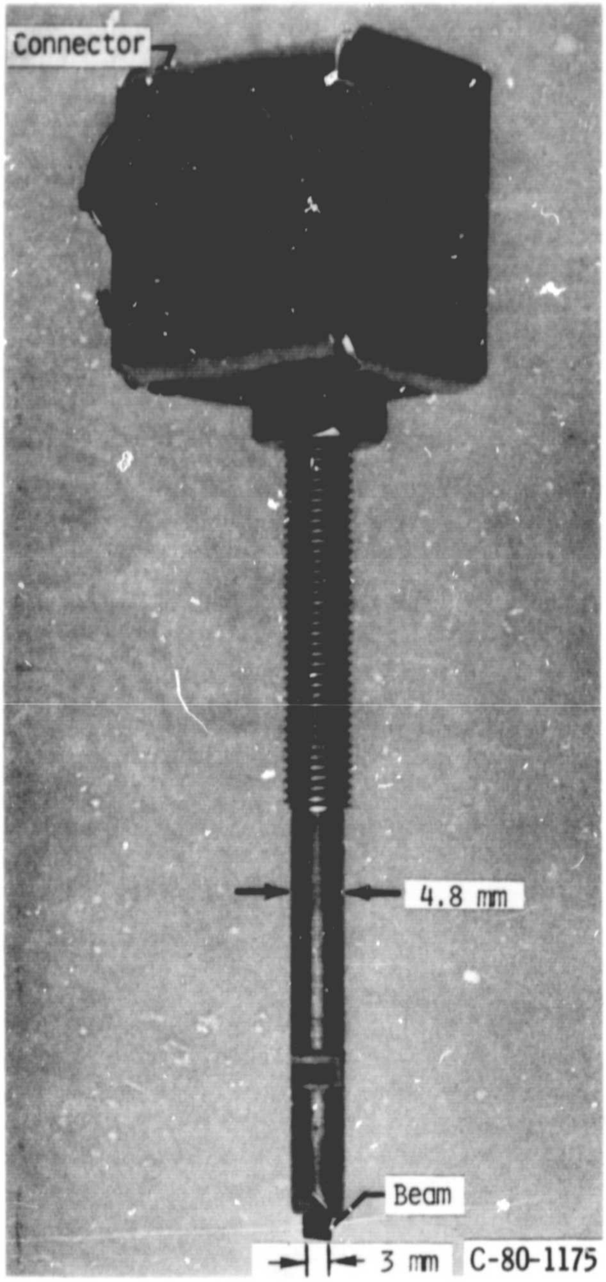
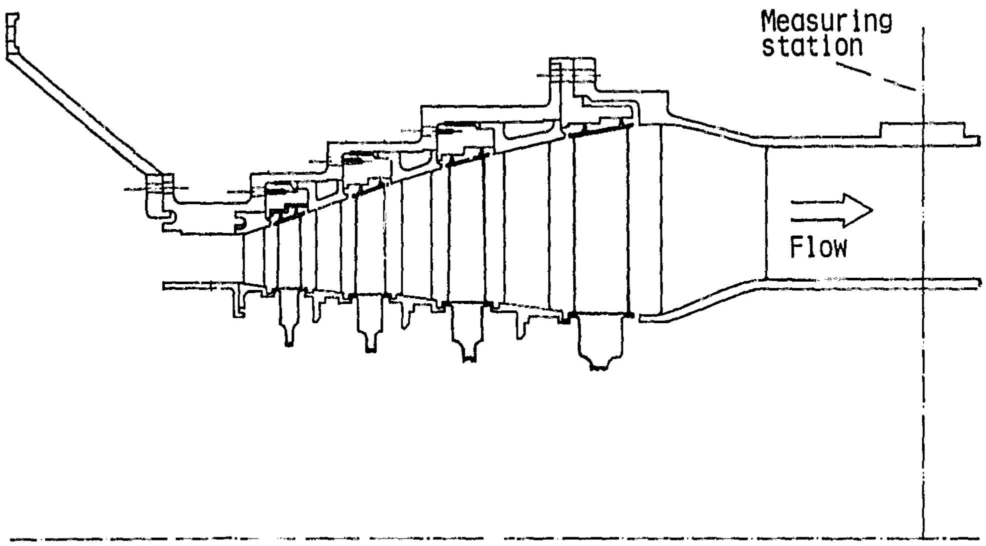
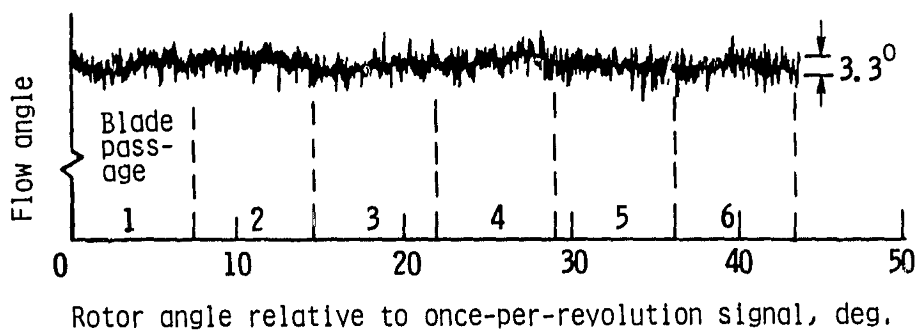


Figure 8. - Unsteady flow measurement probe for use in bypass duct of turbofan engine.

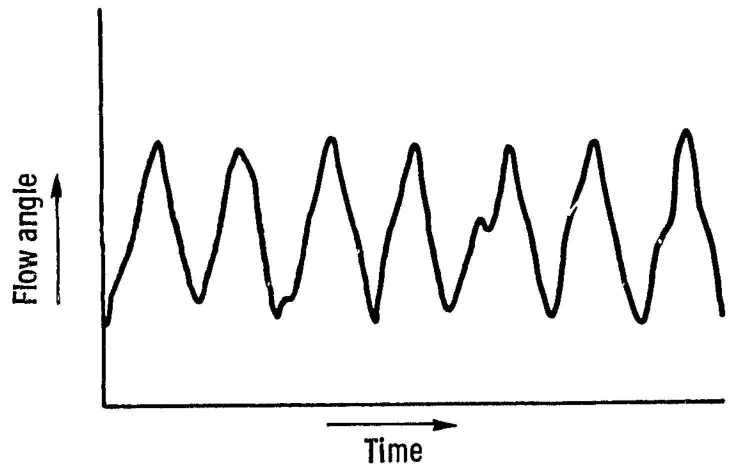


(a) Flow path and measuring station

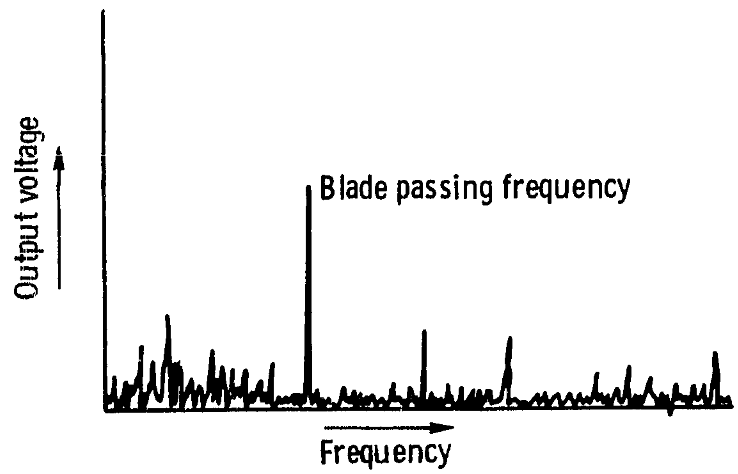


(b) Dynamic flow angle

Figure 9. - Dynamic flow angle measurement behind turbine rotor.



(a) Dynamic flow angle.



(b) Frequency spectrum

Figure 10. - Dynamic flow angle measurement behind fan rotor in turbofan engine.

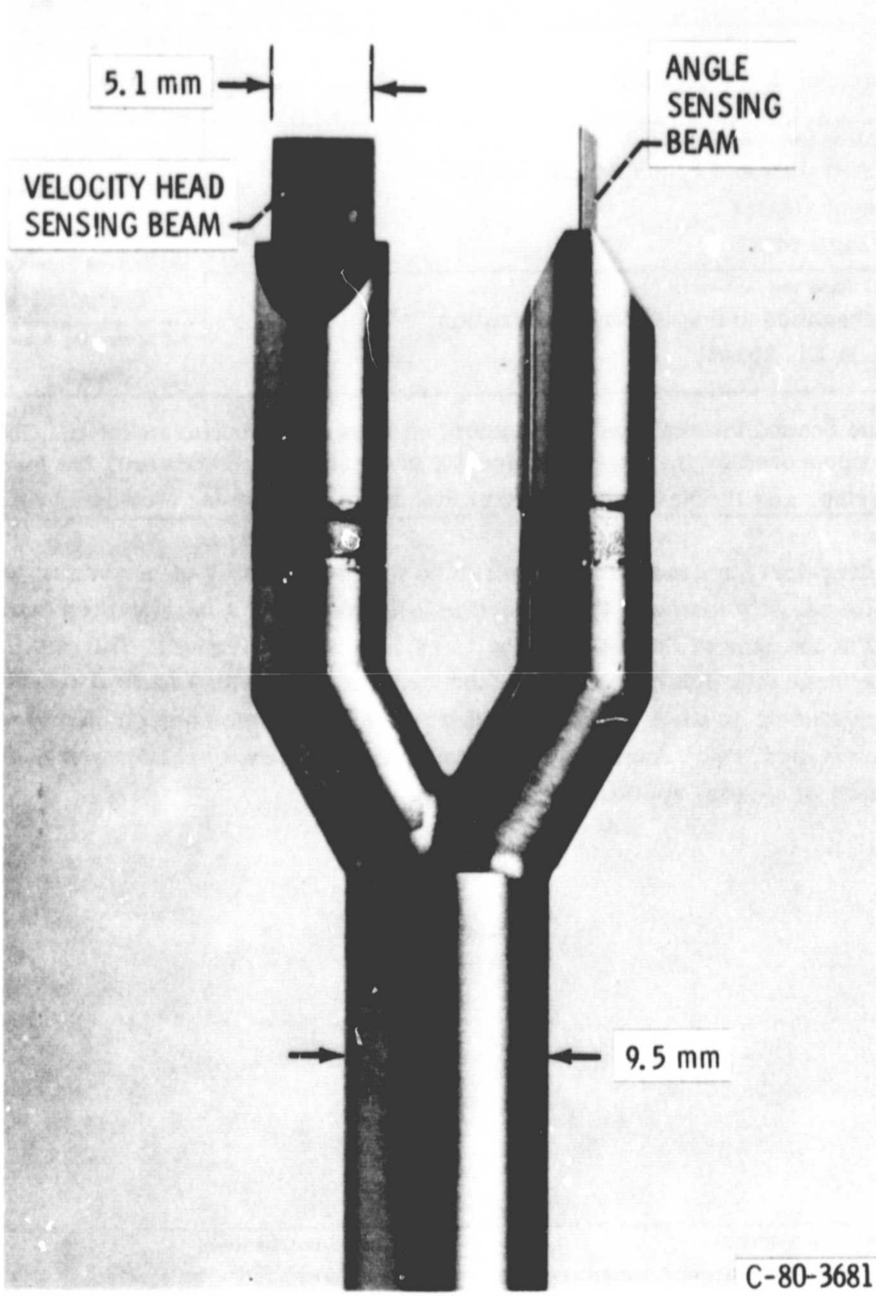


Figure 11. - Unsteady flow angle probe for use in turbofan engine inlet.

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16. Abstract

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